Sequestration - Progress along the road mapped
An update on the DOE roadmap process

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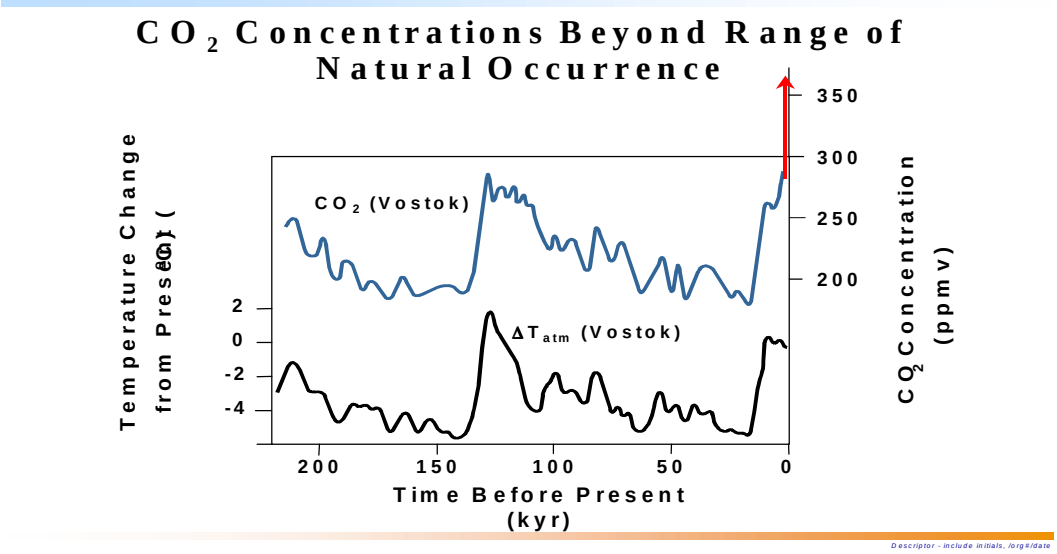
Introduction

The United States Department of Energy has long performed research, development, and demonstration projects focusing on creating less carbon-intensive and more energy-efficient methods of generating energy. Although these activities may help reduce emissions of greenhouse gases (GHG's), given the importance of developing adequate strategies for mitigating against climate changes another parallel strategy may offer significant potential. Carbon sequestration may further reduce the buildup in atmospheric concentrations of greenhouse gases (GHG's).

The Offices of Fossil Energy and of Science jointly developed a document, "Carbon Sequestration Research and Development Report" that identified ideas for sequestration options and that addressed the research and development needs essential to validating these options as useful approaches to managing GHG's. These offices have begun funding R&D addressing the needs identified in the report. This paper seeks to provide a status report on these efforts and to baseline the projects now in place. Both programs must now begin the process of assessing the projects in place and the progress being made toward demonstrating the potential of carbon sequestration technologies.

1. Is the Climate Changing? - The evidence

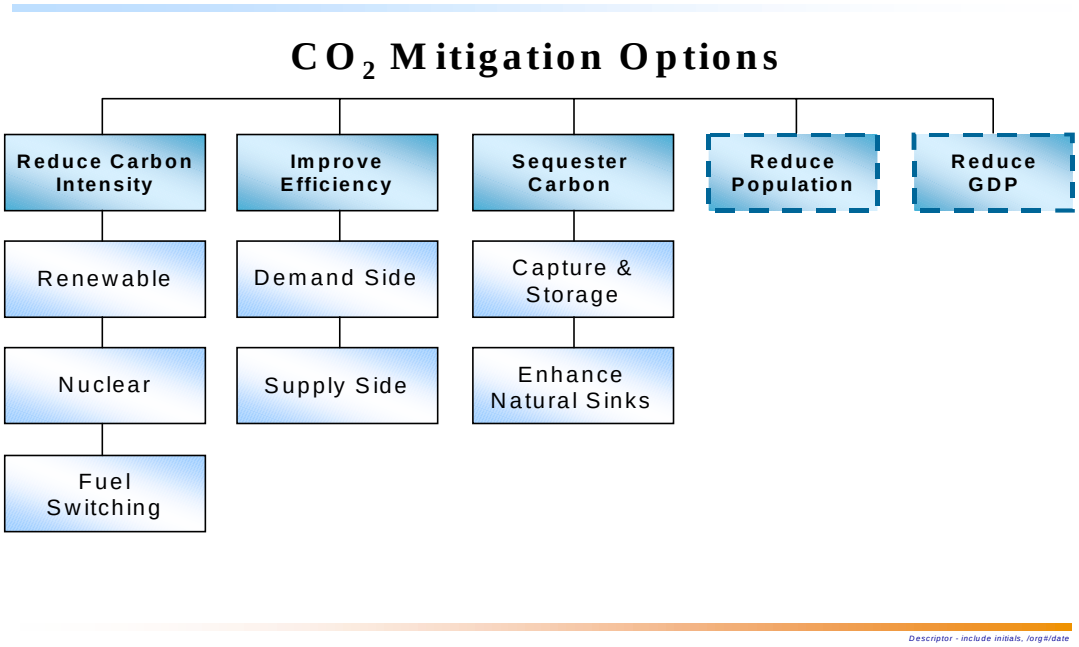
Considerable evidence has accumulated that the climate is indeed changing. Frost dates in the Northern Hemisphere have changed resulting in longer growing seasons. Glaciers are retreating in many places. Figure 1 combines data from Mauna Loa that represents the measured rise in



the concentration of CO2 in the recent past and the derived long-term trends in the CO2 concentration taken from ice core data. The second curve on the figure presents a similar combination of derived and measured temperature over the same time frame. Both curves follow a similar trend - they show a rapid increase in the recent past. Evidence such as this has

prompted the Intergovernmental Panel on Climate Change (IPCC) to accept the position that man is having a discernable impact on the climate.

The potential magnitude of the reductions in GHG emissions is daunting. Projections of increased energy use across the world imply that we may need to reduce carbon emissions as much as 20 gigatonnes of carbon per year (GtC/yr) late in this century to achieve stabilization of the CO2 concentration in the atmosphere. This is independent of the approach used to avoid or capture and sequester carbon. Figure 2 depicts the range of avoidance and sequestration options that are open to us.



The DOE study on carbon sequestration established the following vision and goal:

> **"Possess the scientific understanding of carbon sequestration and develop to the point of deployment those options that ensure environmentally acceptable sequestration to reduce anthropogenic emissions and/or atmospheric concentrations. The goal is to have the potential to sequester a significant fraction of 1 GtC/year in 2025 and 4 GtC/yr in 2050."**

In Figure 2, reducing carbon intensity includes everything from switching to natural gas to using alternative carbon-free energy sources such as generating electricity in a new generation of nuclear power stations or by hydrogen as a fuel. Energy efficiency includes both more efficient power generation and new end-use technologies and highly efficient buildings. Finally, carbon sequestration includes both direct and indirect (terrestrial) approaches. The last two options are not technical options and will not be discussed.

2. Developing a Sequestration Program

In establishing a research and development program for carbon sequestration, the Office of Fossil Energy focused on defining criteria for the success of the program that recognizes that fossil fuels must continue to play a central role in the world energy mix. We believe that energy meet the criteria in Table 1:

Available

- **Abundant**
- **Reliable**

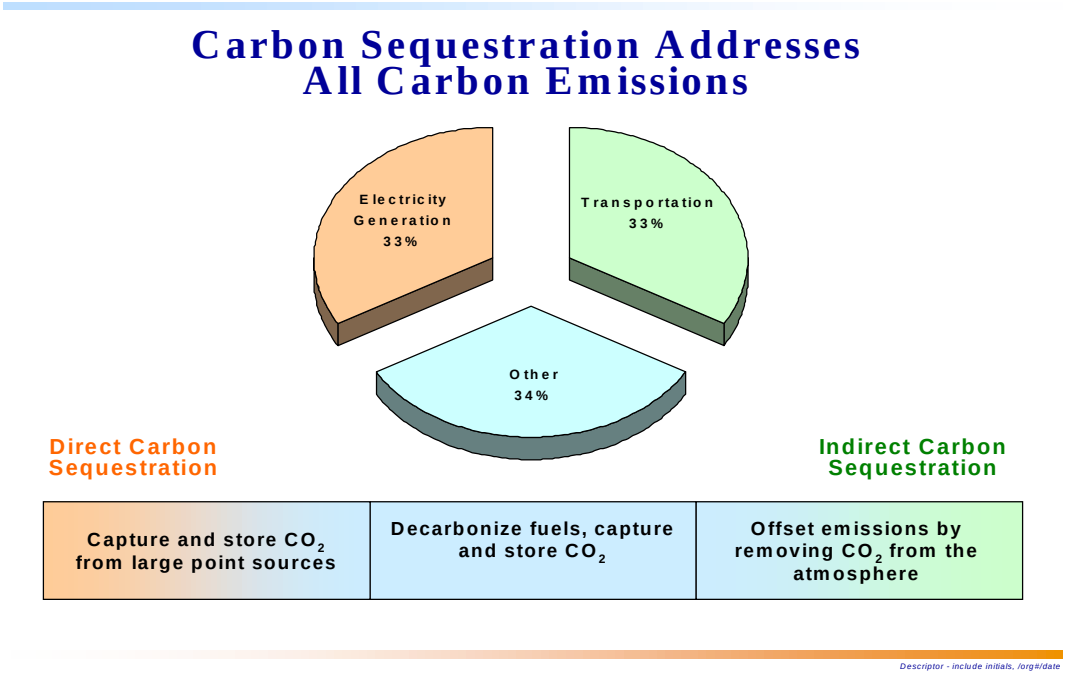
Affordable

- **Ensure America's economic vitality**
- **Fuel future energy requirements**

Acceptable

- **Increasingly clean**
- **Improve air quality**

Fossil fuels are abundant. Significant quantities of coal, oil, and natural gas remain. Projections indicate that these fuels will continue to supply a large portion of energy consumed in the world for years to come. These same projections indicate that other sources of energy, including technologies such as wind turbines, biomass fuels and various solar technologies will provide an increasing amount of energy. There will also be a continued emphasis on reducing the impact of energy production on the environment including ever- tightening air and water quality rules. Potential global restrictions on emissions of greenhouse gases into the environment supports arguments for development of technologies such as carbon sequestration - a suite of technologies that may afford means to manage carbon emissions from all sources (Figure 3).

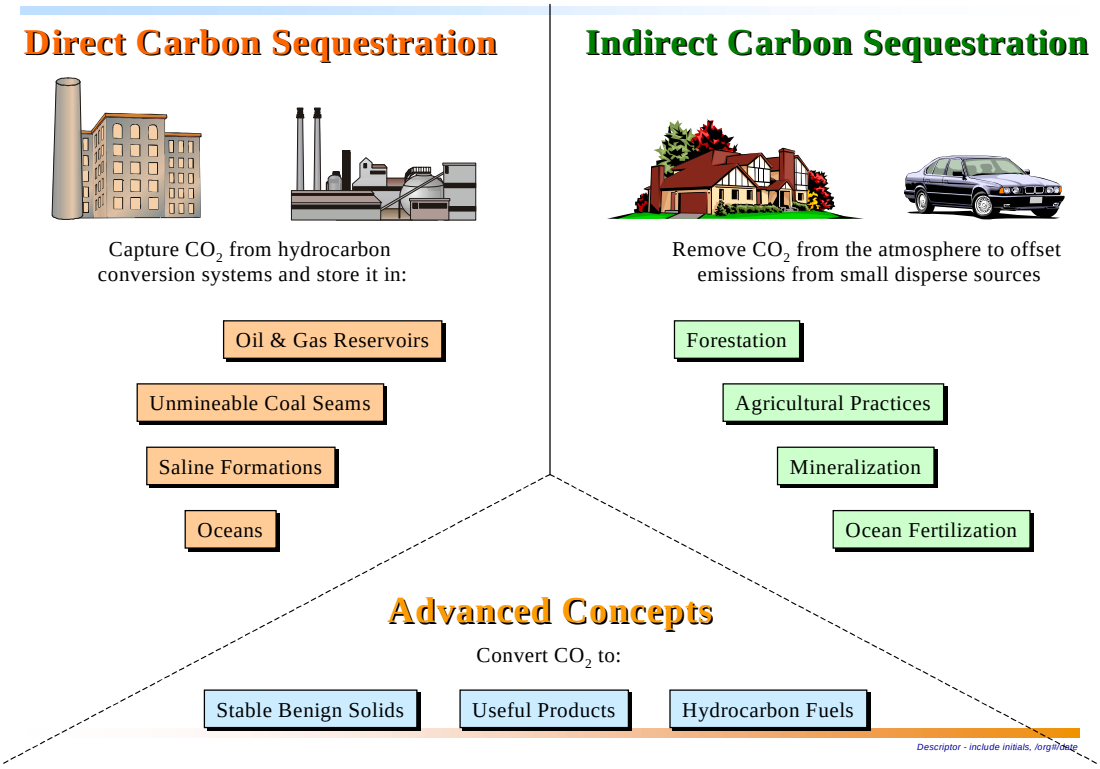


In order to develop a suite of technologies that meet criteria supporting the concept of available, affordable, and acceptable energy, a portfolio of technologies must be created. Table 2 lists key features of the portfolio. Research and development activities once initiated must undergo a process of validation to ensure that they meet the criteria and could lead to a suite of solutions that are consistent with the energy supply and use patterns in the future. As the world currently relies on large, central facilities for power production, separation and capture from such facilities is an essential element that must be explored (Figure 4).

Sequestration Portfolio

- **Several approaches to sequester carbon have been identified.**

- **Validate options by developing the knowledge base and readying technologies for deployment.**
- **Understand the role of carbon sequestration in mitigation strategies.**
- **Separation and capture is a key element of the portfolio.**



To facilitate program planning and to create a balanced portfolio, topical areas of interest were identified. These are given in Table 3. Separation and capture, storage in geologic formations, development of advanced process concepts, process modeling and assessment are particularly key issues for large production facilities located inland. For the oceans and the terrestrial biosphere, the key issues relate to the relationship between the natural carbon cycle and the impact that anthropogenic emissions might have on the functioning of this cycle. These cycles define the capacity of natural systems for indirect sequestration of carbon. There are also crossover topics related to ocean disposal of CO2 captured on-shore and to efficient means to integrate energy production systems with terrestrial sinks.

Research Topical Areas:

- **CO_2 separation and capture**
- **Sequestration in geological structures**
- **Ocean sequestration**
- **Integration of energy production systems with terrestrial sinks**
- **Advanced chemical and biological concepts**
- **Modeling and assessments (crosscutting)**

This program is being pursued in two offices within DOE and similar work is ongoing for some topical areas at other agencies. The Office of Science and the Office of Fossil Energy are both working on aspects of this problem. Office of Science is focusing on research related to the carbon cycle and to the oceans plus supporting basic science in areas relevant to all roadmap topics. The Office of Fossil Energy focuses on: separation & capture, geologic sequestration, technology aspects of other forms of sequestration, and advanced concepts.

Table 4 presents a brief summary of the history of this program within the Office of Fossil Energy.

Assessments Studies	Program Budget Growth
● **January 1997 -MIT White Paper** ● **1997 -PCAST report** ● **1997 - Report: Technical Opportunities to Reduce U.S. Greenhouse Gas Emissions** ● **1998 - 1999 Office of Science/ Fossil Energy report developed** ● **1999 - PCAST international report issued** ● **Program plan looks to 2015**	● **1998 -$1Million for CO2 control (environmental)** ● **1999 - $4 Million budget item** ● **2000 - $9.2 Million to initiate R&D program** ● **2001 - $19.0 Million (est.) to expand program**

3. Description of Current Program Activities

As described in the Table above, a series of solicitations have resulted in selection of a number of R&D contracts aimed at developing sequestration as a viable option for carbon management. The existing portfolio of contracts will be described in brief aligned by topical area.

3.1 CO2 Capture

CO_2 Capture from Flue Gas Using Dry Regenerable Sorbents: Research Triangle Institute, teaming with Church and Dwight, Inc., will develop a simple, low-cost separation technology using regenerable, sodium-based sorbents for removing CO_2 from coal flue gas**.**

CO_2 Selective Ceramic Membrane for Water-Gas-Shift Reaction with Simultaneous Recovery of CO2: Media and Process Technology, Inc. is developing a high temperature CO_2-selective membrane to enhance the water-gas-shift reaction efficiency while recovering CO_2 for sequestration. This project includes the University of Southern California as a partner.

Recovery of CO_2 in Advanced Fossil Processes Using a Membrane Reactor: Research Triangle Institute is developing an inorganic, palladium-based membrane device that can reform hydrocarbon fuels to mixtures of H_2 and CO_2 while separating the high-value H_2.

Evaluation of Coal-Fired Power Plants with Flue Gas Recirculation: Argonne National Laboratory is performing a 2-year study of approaches for retrofitting coal-fired power plants with recirculating technology to concentrate CO_2 for transport to sequestration sites.

Carbon Dioxide Hydrate Process for Gas Separation from Shifted Syngas: Nexant, Inc. will develop and evaluate a process for scrubbing CO_2 using water at near freezing temperatures and at high pressure. This study includes Los Alamos National Laboratory and Simteche as partners.

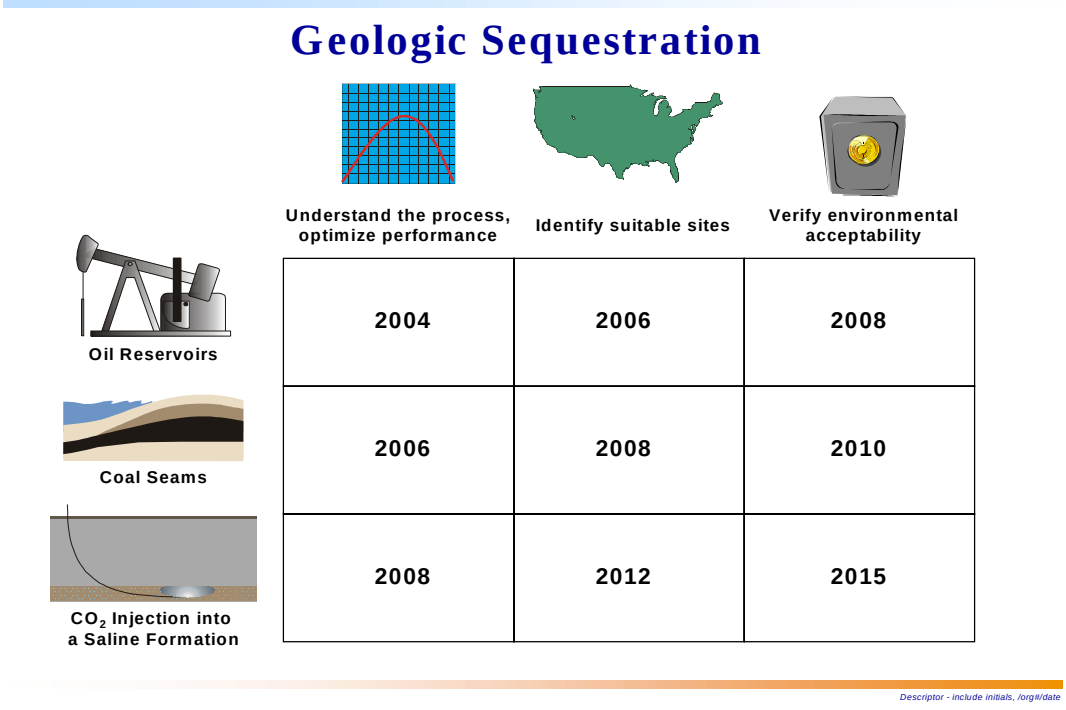
A Novel CO_2 Separation System-- The *"Sorbent Energy Transfer System"* : TDA Research, Inc., in collaboration with Louisiana State University, is developing a system that using gasified coal or natural gas to reduce a metal-oxide sorbent, thereby producing steam and CO_2. The steam is condensed and the CO_2 is sequestered using compressed energy.

CO_2 Separation Using Thermally Optimized Membranes : Los Alamos National Lab and Idaho National Engineering and Environmental Laboratory, in collaboration with the University of Colorado, Pall Corp., and Shell Oil Co., are undertaking a 3-year effort to develop and improved high-temperature polymer membranes for separating CO_2 from methane and natural gas.

Vortex Tube Design and Demonstration : The Idaho National Engineering and Environmental Laboratory was selected to perform a 3-year project to develop and demonstrate a novel gas-liquid contactor that creates a whirlwind-like vortex for separating CO_2 from natural gas and flue gas. They are working with Purdue University, Pacific Gas & Electric, Southern California Gas, and BP Amoco on this project.

3.2 Geologic Sequestration

The geologic sequestration portion of the program aims to identify reservoir capacity across the US, to understand the process and optimize performance, and to validate that geologic sequestration meets the programmatic criteria for acceptable long-term storage. This approach is shown in Figure 6 below.



The projects currently underway within this topic include:

University of Utah: Study CO_2 storage in deep saline reservoirs in the Colorado Plateau and Rocky Mountain region.

Geological Survey of Alabama : Study CO_2 storage in the Black Warrior coal-bed methane region of Alabama.

Advanced Resources International: Test enhanced coal bed methane recovery technology to store CO_2 in coal seams in the San Juan Basin.

Texas Tech University: Develop nuclear magnetic resonance well-logging techniques to identify suitable geological formations for long-term CO_2 storage.

Sequestration of CO_2 in a Depleted Oil Reservoir: A Comprehensive Modeling and Site Monitoring: Sandia and Los Alamos National Laboratory will collaborate with Strata Production Company and the New Mexico Petroleum Recovery Center. They are conducting a 3-year project to investigate down-hole injection of CO_2 into depleted oil reservoirs to help validate safe, long-term storage options.

Lawrence Berkeley, Lawrence Livermore, and Oak Ridge National Laboratories: These laboratories are collaborating with Chevron, Texaco, Pan Canadian Resources, Shell CO_2 Co., BP-Amoco, Statoil, and Alberta Research Council. The team has recently started a 3-year study of geological sequestration of CO_2 in formations such as brine reservoirs, depleted oil reservoirs, and coal beds.

3.3 Terrestrial Sequestration

Research work under this topic includes work at the Office of Science (Enhancing the Natural Terrestrial Cycle). This research will identify ways to enhance carbon sequestration of the terrestrial biosphere through CO_2 removal from the atmosphere by vegetation and storage in biomass and soils. This includes the development of effective approaches to enhance potential sequestration in part through advances in the fundamental understanding of biological and ecological processes and the formation of soil organic matter in unmanaged and managed terrestrial ecosystems, including wetlands. It also includes efforts to understand ecological consequences of carbon sequestration. The research strategy focuses on those properties and processes of ecosystems for which alteration can offer significant potential for enhancing the net sequestration of carbon.

Relevant technical areas of research include: (1) increasing the net fixation of atmospheric carbon dioxide by terrestrial vegetation with emphasis on physiology and rates of photosynthesis of vascular plants, (2) retaining carbon and enhancing the transformation of carbon to soil organic matter; (3) reducing the emission of CO_2 from soils cause by heterotrophic oxidation of soil organic carbon; and (3) increasing the capacity of deserts and degraded lands to sequester carbon.

In addition, there are ongoing projects in the portfolio of the Office of Fossil Energy. This later group includes:

Stephen F. Austin State University: Evaluate reclamation and reforestation of abandoned mine lands in the Appalachian region to sequester carbon and develop a CO_2 trading system.

Tennessee Valley Authority: Evaluate the application of coal combustion byproducts as soil amendments to reclaim abandoned mine lands for subsequent CO_2 storage.

Enhancing Carbon Sequestration and Reclamation of Degraded Lands: Oak Ridge/Pacific Northwest National Laboratories are working with The Ohio State University and Virginia Polytechnic Institute. This team will conduct a 2-year effort to investigate the use of soil amendments from coal plants, paper mills, and sewage treatment to improve CO_2 sequestration of degraded lands.

3.4 Ocean Sequestration

Research work under this topic includes work at the Office of Science

(Carbon Sequestration in the Oceans). The ocean represents a large potential sink for sequestration of anthropogenic CO_2 emissions. Two strategies for enhancing carbon sequestration are 1) the enhancement of the net oceanic uptake from the atmosphere by fertilization of phytoplankton with micro- or macronutrients, and 2) the direct injection of a relatively pure CO_2 stream to ocean depths great than 1000 m. Sources of CO_2 for direct injection might include power plants, industries or other sources. The long term effectiveness and potential environmental consequences of ocean sequestration by either sequestration strategy are unknown.

Research areas relevant to DOE's mission in carbon management include: 1) environmental consequences of long term ocean fertilization; 2) effectiveness of ocean fertilization on a large scale; 3) environmental consequences of direct injection of CO_2 into the ocean in midwater or deep sea habitats; and 4) effectiveness of direct injection of CO_2 for carbon sequestration.

In addition, ongoing projects in the portfolio of the Office of Fossil Energy include:

Monterey Bay Aquarium Research Institute: Apply remotely operated deep-sea vehicle technology, time-lapse cameras, and other techniques to determine fate of CO_2 in oceans.

Washington University: Conduct analyses of frozen CO_2 deposits (hydrates) on the sea floor.

CO_2 Ocean Sequestration Field Experiment: Collaborative effort between NETL, Japan, Norway, Canada, and ABB. The purpose of this study is to study deep water storage of CO_2 off the coast of Keahole Point, Hawaii by injecting CO_2 at a depth of about 1000 meters.

Accelerated Carbonate Dissolution as a CO_2 Capture and Sequestration Strategy: Lawrence Livermore National Laboratory is collaborating with the U.S. Geological Survey and the Monterey Bay Aquarium Research Institute. They are performing a 2-year study of the formation and stability of CO_2 hydrates related to ocean sequestration.

Large-Scale CO_2 Transportation and Deep Ocean Sequestration: MTI is teaming with the Hawaii National Energy Institute to study the viability of large-scale CO_2 transportation and systems for deep ocean sequestration.

3.5 Advanced Concepts

This topic includes on-going work plus the results of a series of small research grants that were awarded early in the program. The intent of these early rounds was to generate ideas that might catalyze later submissions for larger-scale R&D projects. Projects recently initiated include:

The Ohio University: Study the use of organisms in specially designed bio-reactor to enhance the photosynthetic conversion of CO_2.

Physical Sciences: Develop technologies that use selected species of micro-algae to photosynthesize CO_2 from power plant flue gas.

Enhancement of CO_2 Emissions Conversion Efficiency by Structure Microorganisms: The Idaho National Engineering and Environmental Laboratory is teaming with Montana State University and the University of Memphis. They are conducting a 2-year study of ways to grow microorganisms known as cyanobacteria as “biofilms” to capture and convert CO_2 via photosynthesis.

This next list of projects represents those recent completed under the first call for novel concepts:

McDermott Technologies - *“Large-Scale CO_2 Transportation and Deep Ocean Sequestration”*

Louisiana State University - *"pH-Neutral Concrete for Attached Microalgae and Enhanced CO_2 Capture"*

Northwest Fuel Development - *"Sequential CO_2 Removal from Stack Gases and Sequestration Using Coal Seams"*

University of Texas at Austin - *"Optimal Geological Environments for CO_2 Disposal in Saline Aquifers in the U.S."*

Battelle Columbus - *" Experimental Evaluation of Chemical Sequestration of CO_2 in Deep Aquifer Media"*

University of North Dakota EERC - *"Novel Systems for Sequestering and Utilizing CO_2"*

Research Triangle Institute - *"Recovery of CO_2 in Advanced Fossil Processes Using a Membrane Reactor"*

Michigan Technological University - *" Bioscrubber for Greenhouse Gas Control"*

Air Products & Chemicals - *"CO_2 Capture from Industrial Process Gases by High-Temperature Pressure Swing Adsorption"*

Tampa Electric Company - *"Removal and Recovery of CO_2 from Syngas and Acid Gas Streams in an IGCC Power Plant for Reduction of Greenhouse Gases"*

TDA Research - *"A Novel CO_2 Separation System"*

Institute for Environmental Management - *"Landfill Operation for Carbon Sequestration and Maximum Methane Emission Control"*

Finally, we have stressed the need for the parallel development of modeling and assessment capabilities.

3.6 Modeling and Assessment

Carnegie Mellon University: Develop a state-of-the-art computer model to assess CO_2 sequestration options and costs on a local, regional, and national level.

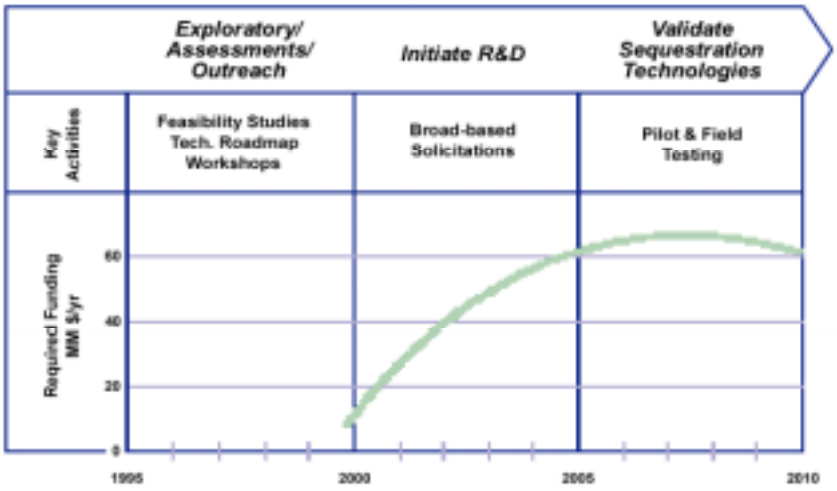
University of Kansas: Develop a digital database that catalogs CO_2 source-to-sequestration information in five midwestern states (IL, IN, KY, KS, and OH).

In addition to these efforts, work will continue on cost and performance assessments of technology options continues throughout program and represents a key step in refining criteria and in directing program. Data will be available for independent evaluations of potential and risk of options within the limits of proprietary rights. Results of on-going assessment and communications efforts may redirect program activities. The on-site research organization at NETL will be conducting research and development that addresses key long-term issues in sequestration. These studies will complement some of the activities currently ongoing. In other cases, they will define new directions for the R&D effort. Modeling and assessment efforts will address the complete portfolio of Fossil Energy funded work and will evaluate progress made elsewhere under other funding for its impact on this program.

4. Summary

In summary, the FE R&D program is a science- and technology-based research effort to guide long-term sequestration technology development. The carbon sequestration program expands options for dealing with GHG's. The approach being taken is designed to validate concepts and achieve benefits. Figure 7 provides a conceptual view of the funding trajectory for this effort.

Program Phases & Proposed Budgets



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Successful demonstration of sequestration technologies provides an alternative to expensive changes in the energy infrastructure. Indeed, the capability to capture and sequester large amounts of carbon for long periods of time could be the only practical solution if drastic reductions are needed. Compared to other means to reduce carbon emissions, successful development of low-cost sequestration could provide an economic benefit of billions of dollars.